Dual-Spacecraft Radio Metric Tracking

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When two interplanetary spacecraft lie along similar geocentric lines of sight, navigational advantages may be achieved by navigating one spacecraft with respect to the other. Opportunities to employ this technique will become more common: the two Viking spacecraft will be within two degrees of each other for the last seven months of their cruise phase; the two Mariner Jupiter/Saturn 1977 (MJS'77) spacecraft will be within three degrees of each other for the last three years of their mission. This article describes the advantages of this technique in both conceptual and mathematical terms and discusses the various data types that might be formulated. The opportunities for testing and utilizing this technique are also outlined.

I. Introduction

Two spacecraft often approach to within a few degrees of each other in the sky. This will be especially true during the coming decade, when both the Viking and MJS'77 missions will involve two spacecraft that virtually "fly in formation" to their target planets. Such occurrences offer unusual navigational opportunities, since when the two spacecraft are tracked from neighboring ground sites, many of the error contributions to the range and doppler data will be common to both spacecraft. If the data types for one of the spacecraft are subtracted from the corresponding data types for the other spacecraft, new data types can be formed in which these common error sources tend to cancel out. Specifically, the sensitivity to antenna site location, UT1, polar motion, troposphere, ionosphere, space plasma, and sometimes instrumental effects can be significantly reduced (Fig. 1). The information retained by the new data types will include the differences in right ascension and declination of the two spacecraft as well as the difference in geocentric range rate (differenced doppler data) or the difference in geocentric range (differenced range data). Under certain conditions, relatively error-free determinations of these quantities should improve trajectory estimates.

In addition, a new navigation data type, differential very long baseline interferometry (ΔVLBI), is now in early stages of experimental development and should provide another and perhaps more accurate means of navigating one spacecraft with respect to another. As presently conceived, this data type will be formed by alternately pointing a single pair of antennas (long baseline) at two nearby celestial radio sources and performing conventional VLBI observations on each source. If corresponding VLBI data types for the two radio sources are differenced, mutual errors are cancelled, and the resultant data types provide a precise measure of the angular separation of the two sources.

II. Applications of Dual-Spacecraft Tracking

It has been previously noted (Ref. 1) that dual-spacecraft tracking offers potential scientific benefits when two spacecraft are extremely close to another planet. If one planetary orbiter is tracked relative to another orbiter, the gravitational field of the planet can be more accurately determined; if a planetary atmospheric probe is tracked relative to another probe, orbiter, or flyby, the atmospheric dynamics of the planet can be more easily deciphered. In these particular applications, the two spacecraft would probably have such a small angular separation that it would be possible to simultaneously track both spacecraft from a single antenna or antenna pair (long baseline), providing even better cancellation of platform parameter and transmission media effects. Some cancellation of instrumental errors would also occur, as much of the ground instrumentation would be used in common by the two spacecraft signals.

Applications of dual-spacecraft tracking also arise when one or both of the spacecraft are in the cruise phase of their flights. Such a technique would afford some relief from the problems incurred in short arc trajectory estimation, since the limiting error sources are generally platform parameter and transmission media effects. If the orbit of one of the two spacecraft is well known from a long arc solution, then dual-spacecraft tracking will provide better short arc solutions for the second spacecraft's orbit than could be obtained by conventional means. Short arc solutions are especially important to spacecraft navigation after a disruptive influence to the orbit of a spacecraft, such as a maneuver, an encounter, or a sudden gas leak.

When a mission involves two spacecraft which encounter the same planet within a short time span, the first spacecraft to arrive may be used to guide the second to a much more accurate encounter if the planet's ephemeris is not well known. That is, normal doppler tracking can tie the first spacecraft to the planet very precisely during that spacecraft's encounter. Then dual-spacecraft tracking can tie the two spacecraft together, and hence tie the second spacecraft to the planet well before its encounter. This technique can become even more powerful when the first spacecraft to arrive is a planetary orbiter, providing a constant "homing" beacon for navigating the second spacecraft.

Dual-spacecraft tracking also offers a partial solution to the problem of estimating small spacecraft declinations. At times of low spacecraft declination, determinations of declination with conventional data types are plagued not only by a lack of sensitivity to declination but also by increased sensitivity to the effects of spin radius errors and atmospheric/ionospheric modeling errors (Ref. 2). With dual-spacecraft data types the insensitivity to declination still remains, but the corrupting effects of spin radius errors and transmission media mismodeling are greatly reduced.

Because of the inherent accuracy of the dual-spacecraft data types, the required number of tracking passes for some spacecraft might be reduced, thus easing the strain on the DSN antenna schedule. For example, in the case of lengthy dual-spacecraft missions, navigation needs might be adequately satisfied during sizable portions of the missions by tracking only one of the spacecraft by conventional means while tracking the other exclusively by dual-spacecraft techniques. In order to provide estimates of the two spacecraft orbits that are of comparable accuracy, the second spacecraft would not need to be tracked as often.

One other efficient characteristic of dual-spacecraft data types should also be noted. Since transmission media effects tend to cancel, low elevation angle dual-spacecraft observations are much more useful than low elevation observations of a single spacecraft.

When dual-spacecraft tracking is performed, the conventional data types need not always be differenced to accrue some navigational advantage. If only one of two nearby spacecraft possesses a means of calibrating the effects of charged particles along the line of sight to that spacecraft (S/X or DRVID), the calibration could also be used to correct the radio metric data from the other spacecraft. During the Viking and MJS'77 missions, both interplanetary spacecraft associated with each mission will possess S/X capability, but there will be only a single S/X ground receiver for each 120-deg longitude sector. Since each pair of spacecraft will be closely spaced for most of their mission, continuous S/X charged particle calibration for both spacecraft would not be possible unless this technique is applied.

Finally, aside from the possible navigational benefits of dual-spacecraft tracking, we should also note that during planetary encounters, tracking the encountering spacecraft relative to another well-located spacecraft might prove useful to celestial mechanics and occultation experimenters. Since much of the celestial mechanics and occultation information is contained only in short intervals of data, the experiments are very sensitive to any noise contributions to the data. Hence, a data type that is relatively free of transmission media effects may improve the results.

III. Mathematical Description of Dual-Spacecraft Data Types

The information content of dual-spacecraft radio metric data types is easily displayed using a simplified mathematical approach. The range from a tracking station to one spacecraft can be approximately given by (Ref. 3):

$$\rho_1(t) = r_1(t) - z_s \sin\delta_1(t) - r_s \cos\delta_1(t) \times \cos[\omega t + \phi + \lambda - \alpha_1(t)]$$

where

- ρ_1 = range from tracking station to spacecraft (subscript "1" denotes first spacecraft; all distances are in light seconds).
- r_1 = geocentric range of spacecraft
- δ_1 = declination of spacecraft
- α_1 = right ascension of spacecraft
- r_s = distance of tracking station from Earth's spin axis
- z_s = distance of tracking station from Earth's equator
- λ = longitude of tracking station
- ω = Earth's rotation rate
- ϕ = a phase angle which depends on choice of epoch
- t = time past epoch

The range to a second spacecraft (subscript "2") may be similarly written as

$$\rho_2(t) = r_2(t) - z_s \sin\delta_2(t) - r_s \cos\delta_2(t) \times \cos[\omega t + \phi + \lambda - \alpha_2(t)]$$

where for mathematical simplicity the tracking station associated with the second spacecraft has been assumed to be collocated with the tracking station associated with the first spacecraft. If these two expressions are differenced, we create a new data type: dual-spacecraft range. Using the following substitutions:

$$\Delta\alpha = \alpha_2 - \alpha_1$$

$$\Delta\delta = \delta_2 - \delta_1$$

$$\Delta r = r_2 - r_1$$

and neglecting second-order terms in $\Delta\delta$ and $\Delta\alpha$, the dual-spacecraft range data type may be represented as

$$\begin{aligned}\rho_2 - \rho_1 = \Delta r + \Delta\delta[&-z_s \cos\delta_1 + r_s \sin\delta_1 \\ &\times \cos(\omega t + \phi + \lambda - \alpha_1)] \\ &- \Delta\alpha\, r_s \cos\delta_1 \sin(\omega t + \phi + \lambda - \alpha_1)\end{aligned}$$

where for notational convenience, the explicit dependence on time of the spacecraft position parameters has been omitted.[1]

In an analogous manner, we can derive an expression for the dual-spacecraft doppler data type. The approximate range rate from the common tracking station to each spacecraft may be written as:

$$\dot\rho_1 = \dot r_1 + \omega r_s \cos\delta_1 \sin(\omega t + \phi + \lambda - \alpha_1)$$

$$\dot\rho_2 = \dot r_2 + \omega r_s \cos\delta_2 \sin(\omega t + \phi + \lambda - \alpha_2)$$

The dual-spacecraft doppler data type may be represented as[2]

$$\begin{aligned}\dot\rho_2 - \dot\rho_1 = \Delta\dot r - \omega r_s [&\Delta\delta \sin\delta_1 \sin(\omega t + \phi + \lambda - \alpha_1) \\ &+ \Delta\alpha \cos\delta_1 \cos(\omega t + \phi + \lambda - \alpha_1)]\end{aligned}$$

Using these formulas, we can draw some approximate conclusions about what information might be extracted from a single pass of dual-spacecraft data. With either of the dual-spacecraft data types, if the position of spacecraft 1 and the equatorial projection of the geocentric vector to the tracking station are assumed known, the differential right ascension and declination of the two spacecraft may be determined from the amplitudes of diurnal sinusoidal and cosinusoidal variations in the data.

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[1]The same result may be obtained by direct differentiation of the expression for spacecraft range.

[2]In the above expressions for the differenced data types, the diurnal term involving $\Delta\delta$ becomes small at low declinations, and second-order terms in $\Delta\alpha$ and $\Delta\delta$ need to be included to show the correct influence of $\Delta\delta$ on the data. Namely, the quantity $(\Delta\delta^2 + \Delta\alpha^2)(\cos\delta_1)/2$ should be added to the term $\Delta\delta \sin\delta_1$. There are also additional small terms involving $\Delta\dot\alpha$, $\Delta\dot\delta$, and Δr that might be included in the simplified expressions for these data types, but these terms can be neglected in most cases.

Additionally, if the polar component of the observing site position is known, the differential geocentric range between the two spacecraft may be determined from the bias portion of dual-spacecraft range data; similarly, the differential geocentric range rate of the two spacecraft may be determined from the bias portion of the dual-spacecraft doppler data.

The sensitivity of these differenced data types with respect to certain parameters is greatly reduced compared to the original data types; indeed, this property of the dual-spacecraft data types is responsible for much of their navigational value. This might lead one to believe that the information content of these differenced data types might be relatively poor. However, it is a fortunate property of the dual-spacecraft data types that their sensitivity to differential range, range rate, declination, or right ascension is essentially identical to the sensitivity of the original data types to the corresponding absolute spacecraft position parameter (i.e., the partial derivatives are nearly identical).

One of the advantages of dual-spacecraft tracking is that the data types are relatively free of corruption due to troposphere, ionosphere and space plasma, although the explicit cancellation of these effects has not been shown in the simplified derivations above. The experience gained by the JPL VLBI experimenters indicates that this cancellation should be significant up to angular separations as large as 10 deg (Ref. 4). Because the dual-spacecraft data lack sensitivity to atmospheric and ionospheric modeling errors, data acquired at very low elevation angles may be as useful as data acquired at high elevation angles. An example of the cancellation of low elevation transmission media effects for two closely spaced ray paths is shown in Fig. 2. Here, two- and three-way doppler data from Pioneer 10 are being received at two nearby ground stations, DSS 11 and DSS 14. Notice the systematic rise in both sets of doppler residuals at low elevation angles due to a lack of transmission media modeling. When these two data types are differenced (QVLBI), the resulting residuals no longer display this systematic rise. The two ray paths in this case were separated by about 5 km as they passed through the atmosphere and ionosphere. With dual-spacecraft data types, it should be noted that there is no cancellation at all of the space plasma in the geocentric range gap between the two spacecraft and that the cancellation of the uplink transmission media effects will be separated in time by the difference in the round trip light times to the two spacecraft. These error sources may be a problem if the two spacecraft are not at similar geocentric ranges.

Another advantage of dual-spacecraft data types is that the errors in site position coordinates, polar motion, and UT1 also cancel to a high degree. For example, the simplified expression for a single pass of normal doppler data shows that the declination of the spacecraft is principally determined from the amplitude, $\omega r_s \cos \delta_1$, of the diurnal sinusoidal signature in the data. If we solve for only the spacecraft angular position, an error in the assumed spin radius ϵ_{r_s} would produce a compensating error in the determination of declination equal to:

$$\epsilon_\delta = \frac{\cos \delta}{\sin \delta}\left(\frac{\epsilon_{r_s}}{r_s}\right)$$

For a spacecraft with a declination of 20 deg, an error in spin radius of 1 meter would cause an error of 0.1 sec of arc in the determination of declination. Since the error in declination is proportional to cot δ, these errors will be significantly greater for spacecraft with smaller declinations. The right ascension of the spacecraft is determined from the phase angle, $\omega t + \phi + \lambda - \alpha$, of the same sinusoidal signature. An error in station longitude is directly compensated by an equal error in the determination of spacecraft right ascension. A longitude error equivalent to 1 meter at the Deep Space Stations would cause an error of about 0.04 sec of arc in the determination of right ascension. With a full pass of dual-spacecraft doppler data, the differential declination of the two spacecraft is determined from the amplitude, $\Delta\delta\omega r_s \sin \delta_1$, of the diurnal sinusoidal signature in the data. If we solve for only the angular separation of the spacecraft, a percentage error in the assumed value of r_s will in most cases cause a similar percentage error in the determination of $\Delta\delta$. If the two spacecraft are separated by 5 deg, an error in spin radius of 1 meter will cause an error of only about 0.003 sec of arc in the determination of differential declination. Moreover, this error is nearly independent of the declination of the spacecraft.[3] The differential right ascension of the two spacecraft is determined from the amplitude, $\Delta\alpha\omega r_s \cos \delta_1$, of the diurnal cosinusoidal signature in the data. Here again, a percentage error in r_s will cause a similar percentage error in the determination of $\Delta\alpha$. That is, an error in spin radius of 1 meter will also cause an error of about 0.003 sec of arc in the determination of differential right ascension. It could also be shown that station longitude errors generally have little effect on the determination of $\Delta\delta$ or $\Delta\alpha$.

[3]Second-order terms in $\Delta\alpha$ and $\Delta\delta$ need to be considered at low declination. In this case, estimates of $\Delta\delta$ can be corrupted by spin radius errors and other error sources if δ_1 and $\Delta\delta$ are nearly equal in magnitude but opposite in sign.

Last, we should mention that dual-spacecraft data types are subject to two of the same problems that plague conventional radio metric data types: unmodeled accelerations and zero declination singularities (Ref. 2). Not surprisingly, these problems may be alleviated by methods similar to those used with the more conventional data types.

Unmodeled accelerations corrupt the conventional tracking data types principally through the geocentric range and range rate contributions to the data types. If the same spacecraft is simultaneously tracked from two widely separated tracking stations[4], differencing of the corresponding data types from the two stations provides new data types (QVLBI range and doppler) that are free of geocentric range and range rate terms and hence relatively uncorrupted by unmodeled accelerations. With dual-spacecraft data types, the effects of unmodeled accelerations enter the data types mainly through the terms involving differential geocentric range and range rate. These terms may be eliminated in an analogous manner to the case of a single spacecraft. That is, if the same two spacecraft are simultaneously tracked by two separate pairs of tracking stations, the dual-spacecraft data types gathered by these antenna pairs may be differenced to cancel the geocentric terms and hence cancel most of the effects of unmodeled accelerations. This dual-spacecraft tracking technique will be referred to as differential QVLBI (ΔQVLBI).

With conventional navigation data types, low declination observations adversely affect determinations of declination for two reasons: (1) the effects of certain systematic error sources are greatly magnified, especially where diurnal error signatures are exhibited as is the case with spin radius errors and atmospheric/ionospheric mismodeling; and (2) the data types become very insensitive to declination. With dual-spacecraft tracking, we have already noted that errors incurred in the estimation of differential declination due to errors in tracking station coordinates remain at rather low levels in most situations. In addition, atmospheric and ionospheric effects are greatly reduced. However, the dual-spacecraft data types do become very insensitive to differential declination at low declinations, so only part of the low declination problem is avoided. With conventional data types, the problem of determining declination at low declinations can be greatly alleviated by the use of "simultaneous" ranging (QVLBI range). With dual-spacecraft data types, "simultaneous" differential ranging (ΔQVLBI range) offers an answer to the low declination problem. This is an obvious consequence of the fact that the declination of each of the two spacecraft would be well determined if the raw ranging data were used to independently create a QVLBI range data type for each spacecraft.

[4]Either by simultaneous two-way and three-way tracking, alternate two-way tracking, simultaneous interference tracking, or simultaneous one-way tracking.

IV. Differential Very Long Baseline Interferometry

Differential very long baseline interferometry (ΔVLBI) (Ref. 5) offers an additional and possibly more accurate means of navigating one spacecraft relative to another. Usually ΔVLBI refers to "simultaneously" performing conventional VLBI observations (Refs. 6–8) on a spacecraft and a nearby extragalactic radio source (ERS) and then differencing the corresponding VLBI data types to permit cancellation of common error sources.[5] The resultant data types have high sensitivity to the angular separation of the two radio sources. Such a technique could also be applied to the case where both radio sources are onboard spacecraft.

The present plan of implementing ΔVLBI involves only a single widely separated pair of antennas that move back and forth in unison between two radio sources with a cycle time of a few minutes. Since the VLBI observations of the two sources will be made at slightly different times, some interpolation will be necessary before the differenced data types can be formulated. With present spacecraft, the most useful VLBI data type is "fringe phase."[6] This data type may be thought of as being analogous to (but not identical to) counted cycles of QVLBI doppler. For the case of a monochromatic source, the fringe phase data type is formed by continually measuring the phase difference of the signals being received at the two antennas and counting the total number of cycles of differenced phase incurred since the initial observation time. Because each source is not being continually observed, it is necessary to extrapolate the differenced (fringe) phase through the nonobserving periods without "slipping" any full cycles.

[5]Thus ΔVLBI allows the spacecraft to be accurately navigated with respect to the precision "inertial" reference frame formed by the ERSs.

[6]Fringe rate is not as sensitive to the angular separation of the two radio sources. To obtain accurate VLBI delay measurements, special wide-bandwidth transmitters would have to be installed on the spacecraft.

A simplified mathematical description of the principal information content of the differenced fringe phase data type $\Delta\phi_f$ is given by

$$\Delta\phi_f(t) \approx \mathbf{B}(t) \cdot [\mathbf{e}_2(t) - \mathbf{e}_1(t)] - \mathbf{B}(t_0) \cdot [\mathbf{e}_2(t_0) - \mathbf{e}_1(t_0)] \quad \text{(cycles)}$$

where

$\mathbf{B}$ = the baseline vector in wavelengths

$\mathbf{e}_{1,2}$ = unit vectors that point toward sources "1" and "2"

t_0 = the initial observation time

or

$$\Delta\phi_f \approx -[r_b \sin\delta_1 \cos\theta]\,\Delta\delta - [r_b \cos\delta_1 \sin\theta]\,\Delta\alpha - C$$

where

r_b = the equatorial component of the baseline

θ = the hour angle of source "1" with respect to the meridian intersected by the baseline

C = a nearly constant term which is not very valuable for determining $\Delta\delta$ and $\Delta\alpha$

Differential right ascension and declination can be determined from the amplitudes of the diurnal sin and cosine functions. Note that only the equatorial component of the baseline influences these amplitudes and that the sensitivity to differential declination is small at low declinations.

To demonstrate the inherent accuracy of the differenced fringe phase data type for dual-spacecraft tracking, a computer error analysis was performed.[7] The test case considered involved the Pioneer 10/11 spacecraft pair during the month of April (1974) when the spacecraft were only about 2 deg apart in the sky. The simulation is made even more realistic by the fact that a maneuver was executed on the Pioneer 11 spacecraft at this time, and owing to the slow movement of this spacecraft across the sky, only short arc solutions were available for reestablishing the spacecraft's trajectory after the maneuver. It was estimated that one or two months would be necessary to satisfactorily redetermine the Pioneer 11 trajectory with conventional radio metric data types. This problem could probably have been greatly alleviated if the Pioneer 11 spacecraft had been tracked relative to the well-known trajectory of the Pioneer 10 spacecraft.

Figures 3a and 3b show the results of this error analysis in which ΔVLBI observations on a number of different baselines have been considered. This analysis was performed with a standard least squares batch filter. It was assumed that one measurement of fringe phase was made for each spacecraft every 6 minutes and that the rms error of these phase measurements was 0.1 cycle at S-band. The resulting uncertainties in differential right ascension range from 10^{-4} to 10^{-3} arcseconds after only two hours of successful observation. Even though the two spacecraft were at low declination (≈ -5 deg), the uncertainties in differential declination are surprisingly small, ranging from 5×10^{-3} to 10^{-2} arcseconds after two hours of observation. For comparison, 10^{-3} arcseconds is equivalent to about 4 km at the distance of Pioneer 11 ($\approx$5 AU). Although more complete error analyses are necessary to ascertain ΔVLBI's ability to contribute to the solution of these types of navigation problems, this simple analysis certainly reveals a high potential.

It has been noted that a direct analog of differenced fringe phase might be formulated by utilizing an inherently simpler observational method. With conventional ΔVLBI, the received signals are recorded on magnetic tape and corresponding tapes are later crosscorrelated on a digital computer to determine fringe phase. However, if each time the two antennas were pointed at a particular spacecraft a phase-locked loop at each station was attached to the spacecraft carrier signal, the relative (or fringe) phase of the two received signals could be determined directly. A differenced fringe phase data type might then be constructed in a manner virtually identical to that of conventional ΔVLBI. Unfortunately, the phase-locked loop concept of ΔVLBI has three potential problems, all of which might prevent successful phase extrapolation through nonobserving periods: (1) insufficient accuracy in the relative phase measurements, (2) failure of the phase-locked loop to quickly capture the spacecraft signal, and (3) phase-locked loop transients following acquisition of the signal.

Last, we might compare ΔVLBI with the dual-spacecraft data types obtained by more conventional tracking techniques. To provide a direct mathematical comparison, consider the "conventional" dual-spacecraft data type which can be formed by continuously counting doppler cycles for each of two spacecraft at a pair of nearby antennas and then differencing the cycle counts ("differenced doppler phase"). A simplified mathematical expression for this data type may be constructed from the equation for dual-spacecraft range by subtracting the

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value of dual spacecraft range at the initial observation time, or

$$\Delta\phi_d = [\Delta r(t) - \Delta r(t_0)] + \Delta\delta\,[r_s \sin\delta_1 \cos(\omega t + \phi + \lambda - \alpha_1)] - \Delta\alpha\,[r_s \cos\delta_1 \sin(\omega t + \phi + \lambda - \alpha_1)] - C \quad \text{(cycles)}$$

where

Δr and r_s are now expressed in wavelengths

C = a nearly constant term which is not very valuable for determining $\Delta\delta$ and $\Delta\alpha$

Note that the form of this expression is very similar to that for differenced fringe phase. As with that data type, differential right ascension and declination must be determined from the amplitudes of the diurnal sin and cosine functions. The main difference in this case is that the spin radius has taken the place of the equatorial baseline component. Since the spin radii of the Deep Space Stations are of approximately the same magnitude as the available equatorial baseline components, the two data types should have nearly equal sensitivity to differential right ascension and declination. It should also be pointed out that conventional dual-spacecraft tracking passes will generally be significantly longer than those for ΔVLBI.

We might then ask, what are the advantages of ΔVLBI over more conventional dual-spacecraft tracking techniques? One advantage is that instrumental phase instabilities are far less important. ΔVLBI is corrupted by instrumental phase errors that build up over a fraction of the switching cycle (a few minutes), while instrumental phase errors that are accumulated during the length of a pass (several hours) can affect conventional dual-spacecraft tracking. Another advantage of ΔVLBI is that only near-Earth down-link transmission media effects are significant, and the cancellation of these effects is separated by only a few minutes. With conventional dual-spacecraft data types, the cancellation of the near-Earth down-link transmission media effects is nearly simultaneous, but the cancellation of the near-Earth up-link effects is separated by a differential round-trip light time. Additionally, the distant space plasma effects may not cancel very well, and there will be no cancellation of the space plasma effects in the geocentric range gap between the two spacecraft. Finally, conventional dual-spacecraft data types are sensitive to the effects of unmodeled accelerations, while ΔVLBI data types are not. We should note that if ΔQVLBI dual-spacecraft tracking is performed, the information content of the resulting data types would be nearly identical to that of the corresponding ΔVLBI data types, and the main corruptions of unmodeled accelerations and transmission media effects would vanish. However, the problem of instrumental phase stability would prohibit ΔQVLBI dual-spacecraft tracking from being competitive in accuracy with ΔVLBI. The instrumental stability problem could be greatly alleviated by either (1) installing hydrogen maser frequency standards at the participating antennas, or (2) providing common frequency standards at the closely spaced antenna pairs.[8] Table 1 summarizes the significant error sources that affect all conventional and dual-spacecraft radio metric data types.

V. Opportunities for Dual-Spacecraft Tracking

Since interplanetary spacecraft do not wander far from the plane of the ecliptic, close angular approaches of the geocentric lines-of-sight to two such spacecraft are quite common, although often transitory. In missions that involve two spacecraft, these spacecraft will generally be desirable subjects for dual-spacecraft tracking for a significant fraction of their missions.

The current dual-spacecraft project is the Pioneer 10/11 mission to Jupiter. Even though their Jovian encounters are about a year apart, the two spacecraft are close together in the sky for an extended period. The trajectories of Pioneer 10/11 across the sky are shown in Fig. 4. The angular separation of the spacecraft as a function of time is shown in Fig. 5. From this figure we see that the two spacecraft remain within 10 deg of each other for a period of 9 months. At the time of the Pioneer 10 encounter the separation was about 7 deg; at Pioneer 11 encounter, the separation will be 17 deg. Hence, at these encounters, dual-spacecraft tracking between Pioneer 10 and 11 might be considered as a means of reducing the corrupting influence of transmission media effects on occultation and celestial mechanics experiments. Also noted in Fig. 4 is the fact that the MVM'73 spacecraft closely approached the Pioneer 10/11 pair for a short period of time, with the angular separation of Pioneer 11 and MVM'73 falling below a degree at one point and remaining at less than 10 deg for about half a month. Surprisingly, MVM'73 encountered Mercury during this brief time period.

Figure 6 shows the approximate angular separation of the Viking A and B spacecraft as a function of time. The angular separation of the two spacecraft will be less than 10 deg from a month after the launch of the second space-

[8]A common frequency standard now exists at DSS 42/43, and one will soon be available at DSS 61/63.

craft until the end of the mission. During the 7 months preceding the second encounter, the separation will be less than 2 deg. After the first spacecraft has arrived at Mars, it might provide an excellent "homing" beacon for the second spacecraft.

Figure 7 shows a likely history of the angular separation of the two MJS'77 spacecraft as a function of time. Within a month after the launch of the second spacecraft, the separation has dropped to 10 deg. For the next 4 months it continues to drop to about 2.5 deg. For the remaining 3.3 years of the mission, the separation remains less than 2.5 deg, being about 1.5 deg at the time of the Jupiter encounters and 0.5 deg at the time of the first Saturn encounter (no data for second encounter).

NASA's budget for FY75 proposes a dual Pioneer spacecraft mission to Venus in 1978. One spacecraft will send four entry probes into the Venus atmosphere; the other will be an orbiter. For this mission, dual-spacecraft tracking might be especially useful in determining probe trajectories, which will be used in studies of the Venus atmosphere. In addition, the majority of potential interplanetary missions which might also be funded during the coming decade would probably involve dual spacecraft. For example, Mariner/Jupiter/Uranus (1979), Jupiter Orbiter (1981), Venus Orbiting Imaging Radar (1983), Encke (1984), and Saturn Orbiter (1985).

VI. Demonstration of Dual-Spacecraft Tracking

Although continued analyses and computer simulations should be undertaken to investigate the potential worth of dual spacecraft tracking to interplanetary navigation, the usefulness of these data types will not be proven until demonstrations are performed with actual spacecraft data. A possible source of data for a dual-spacecraft tracking demonstration is previously recorded tracking data. The Pioneer 10/11 spacecraft pair provides the best opportunity for performing such a demonstration. These spacecraft were within 5 deg of each other from December 1973 through June 1974, and within 10 deg through mid-August 1974 (see Fig. 4). Another interesting possibility is the Mariner 6/7 spacecraft pair. Here we might attempt to track Mariner 7 into its Mars encounter by means of dual-spacecraft tracking during the encounter phase of Mariner 6.

The navigational utility of dual-spacecraft tracking might be demonstrated by the following method: Use conventional tracking data to perform accurate long arc solutions for the trajectories of the two relevant spacecraft. Then, using data from only a short segment of that long arc, make two independent estimates of one of the spacecraft trajectories. One of these estimates would utilize only conventional radio metric data; the other would utilize only dual spacecraft radio metric data. The results could then be compared with the corresponding long arc solution. Such a procedure could be repeated a number of times using different pairs of DSN antennas, spacecraft angular separations, and dual spacecraft data types.

VII. Summary

When two spacecraft appear close together in the sky, navigational advantages may be accrued by navigating one spacecraft with respect to the other. If the spacecraft are tracked from nearly colocated antennas, many of the error contributions to the conventional radio metric data types will be common to both spacecraft. Thus, by differencing corresponding data types for the two spacecraft, mutual error sources tend to cancel. The resultant "dual-spacecraft data types" will contain accurate information concerning the relative position of the two spacecraft. "Simultaneous" very long baseline interferometry observations of the two spacecraft could provide even more accurate dual-spacecraft data types. The principal benefits of dual-spacecraft tracking are:

(1) The cancellation of platform parameter and transmission media modeling errors in short arc estimation problems.

(2) Accurate encounter guidance for the trailing spacecraft in dual spacecraft encounter missions.

(3) A partial solution of the low declination problem.

(4) Easing of the strain on the DSN antenna schedule.

Since both the Viking and MJS spacecraft pairs will appear close together in the sky for most of their missions, dual-spacecraft data types might play a useful role in the navigation of these spacecraft. Hence, further investigation of the navigational utility of these data types seems warranted.

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Table 1. Summary of significant error sources in conventional and dual-spacecraft radio metric data types (X = significant)

Significant error sources	Single-spacecraft data types		Dual-spacecraft data types		
	One station	Two-station (QVLBI)	Two-station	Four-station (ΔQVLBI)	ΔVLBI
Troposphere	X	X	[a]		
Ionosphere	X	X	[a]		
Space plasma	X		[a, b]		
Antenna site positions or baseline vector	X	X			
UT1	X	X			
Polar motion	X	X			
Instrumental phase drifts	X	X	X[d, e]	X[c, d]	
Unmodeled Accelerations	X		X		
Zero declination singularity	X	X[f]	X	X[f]	X[f]
Planetary ephemerides	X	X	X[g]	X[g]	X[g]

[a]Can be significant if two spacecraft are not at similar geocentric ranges.

[b]Distant space plasma may be significant.

[c]Effect is not significant if common frequency standards exist at nearby antenna pairs.

[d]Effect can be reduced if hydrogen maser frequency standards are utilized at each antenna.

[e]Footnote c applies if spacecraft are at similar geocentric ranges.

[f]Effect is not significant for QVLBI range, ΔQVLBI range, and ΔVLBI delay data types.

[g]Effect can be reduced for trailing spacecraft in dual-spacecraft missions.

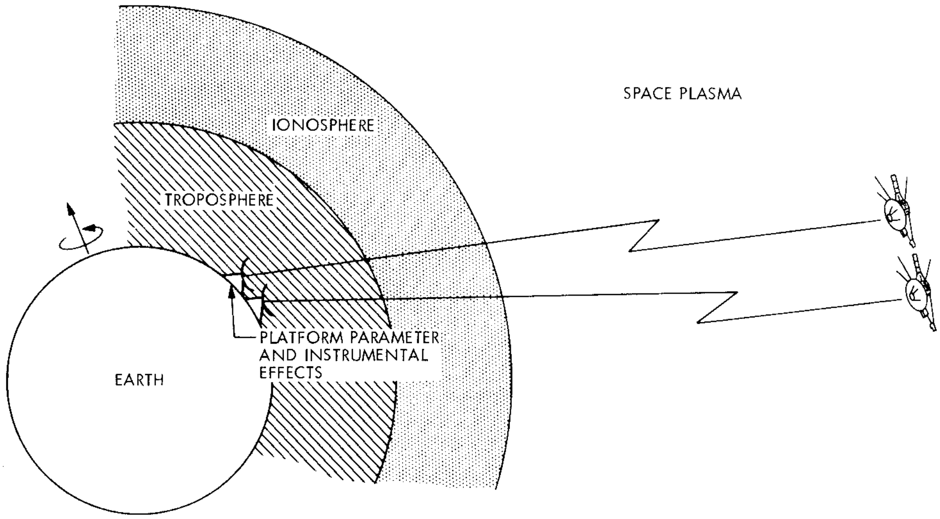

Fig. 1. Dual-spacecraft radio metric tracking: common error sources tend to cancel

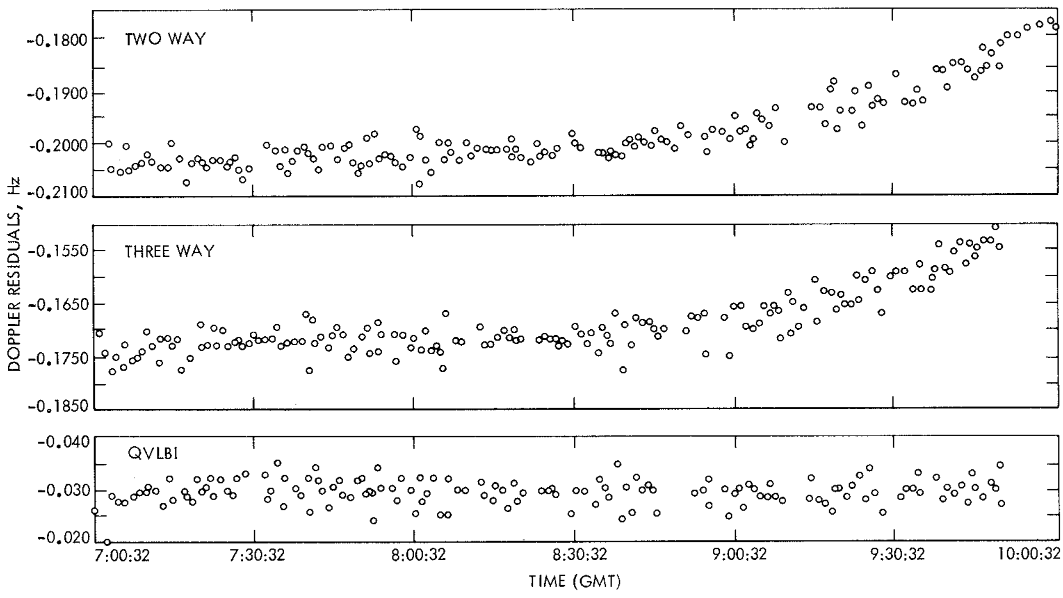

Fig. 2. Cancellation of transmission media effects at low elevation angles (short baseline QVLBI data)

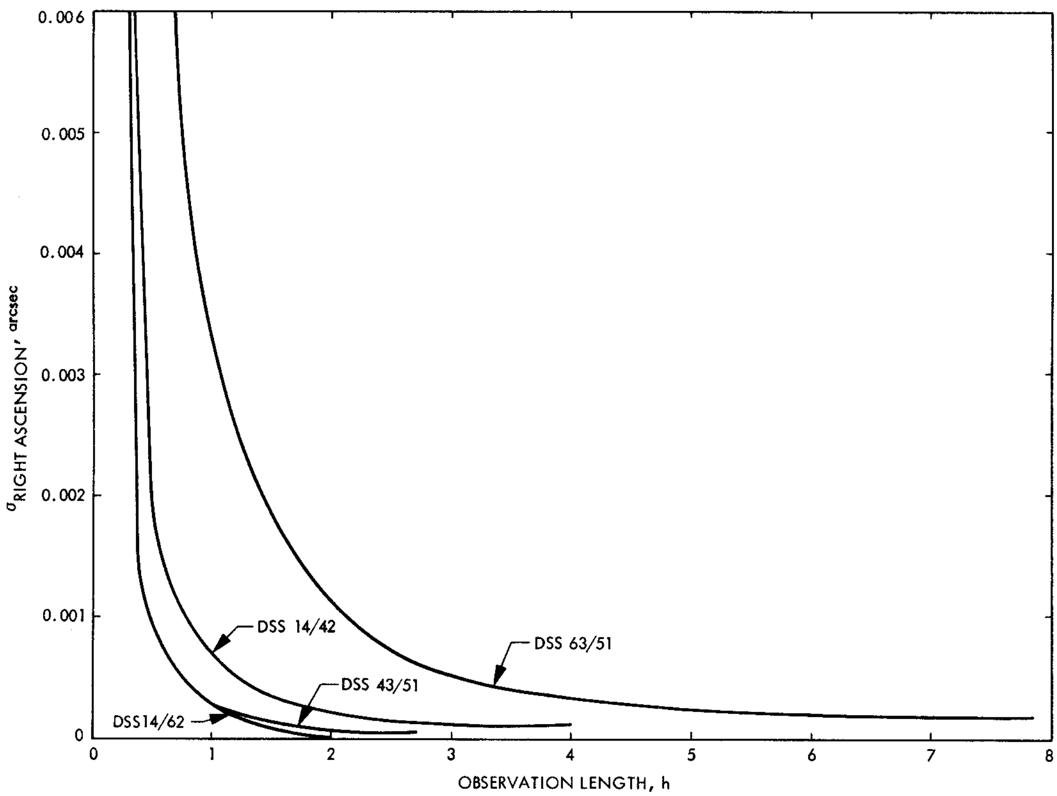

Fig. 3a. Uncertainty in right ascension of Pioneer 11 relative to Pioneer 10 vs VLBI observation length

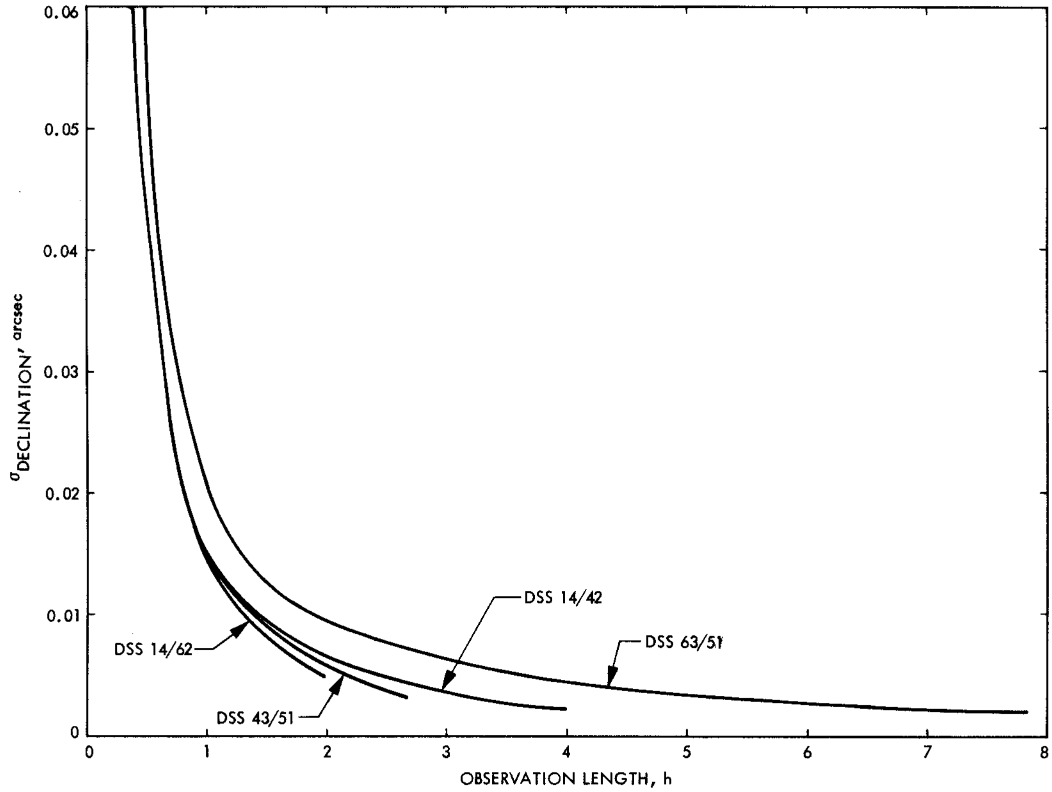

Fig. 3b. Uncertainty in declination of Pioneer 11 relative to Pioneer 10 vs VLBI observation length

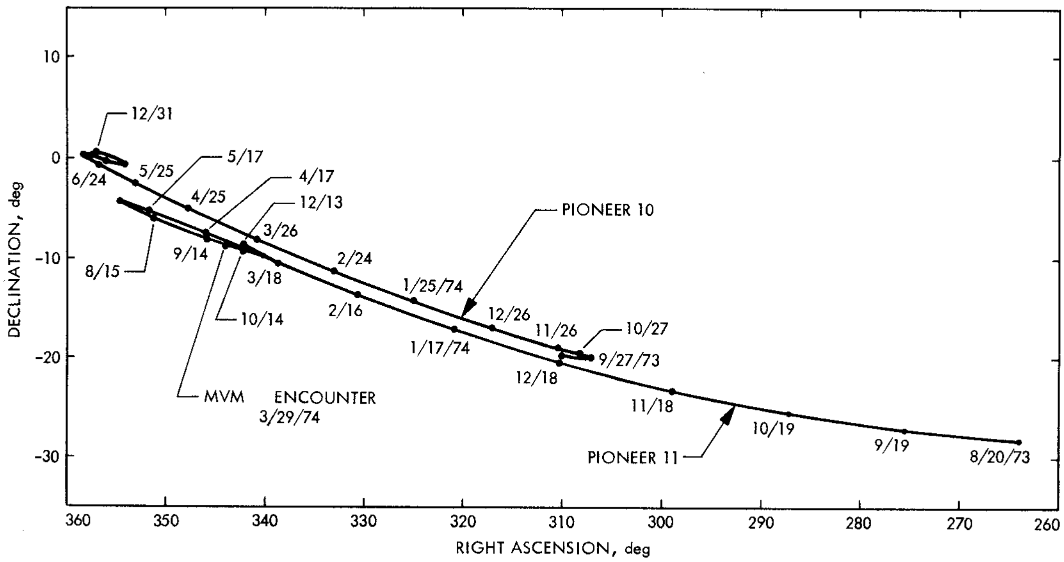

Fig. 4. Angular positions of Pioneer 10 and 11 spacecraft

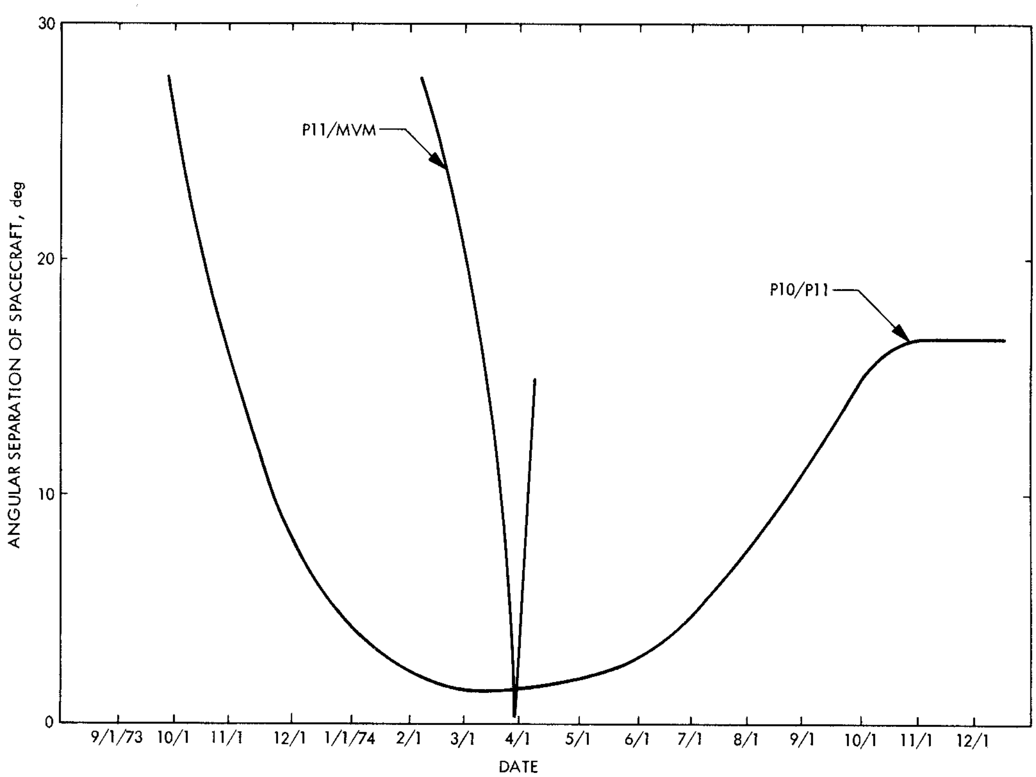

Fig. 5. Angular separations of Pioneer 10, Pioneer 11, and MVM'73 spacecraft

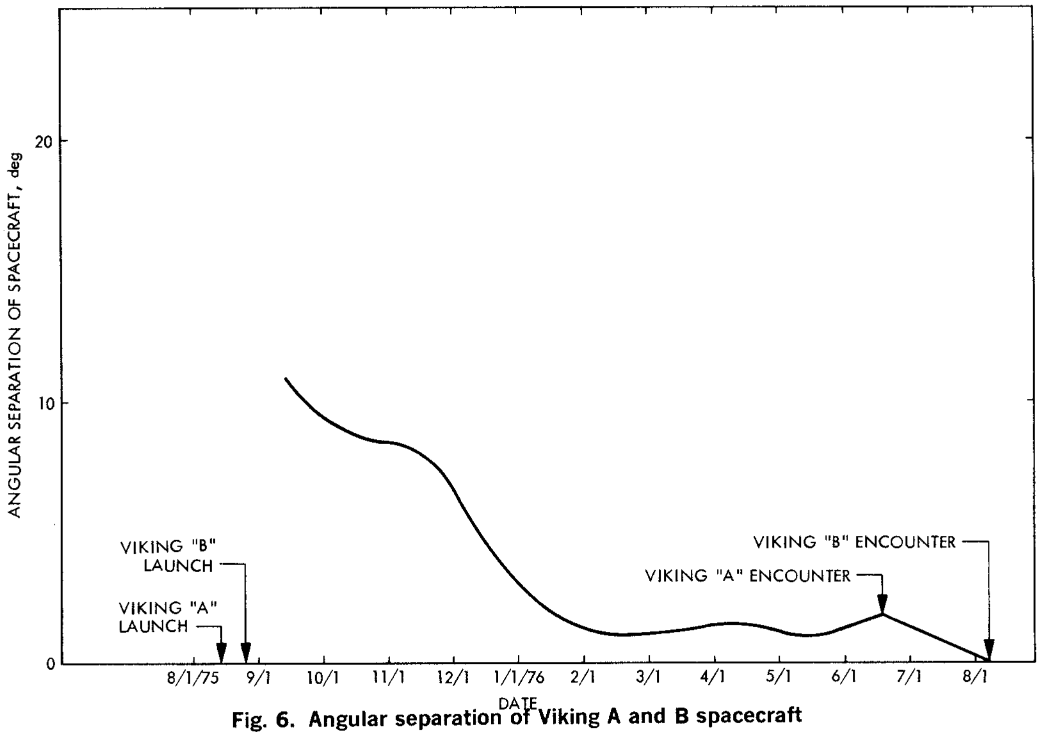

Fig. 6. Angular separation of Viking A and B spacecraft

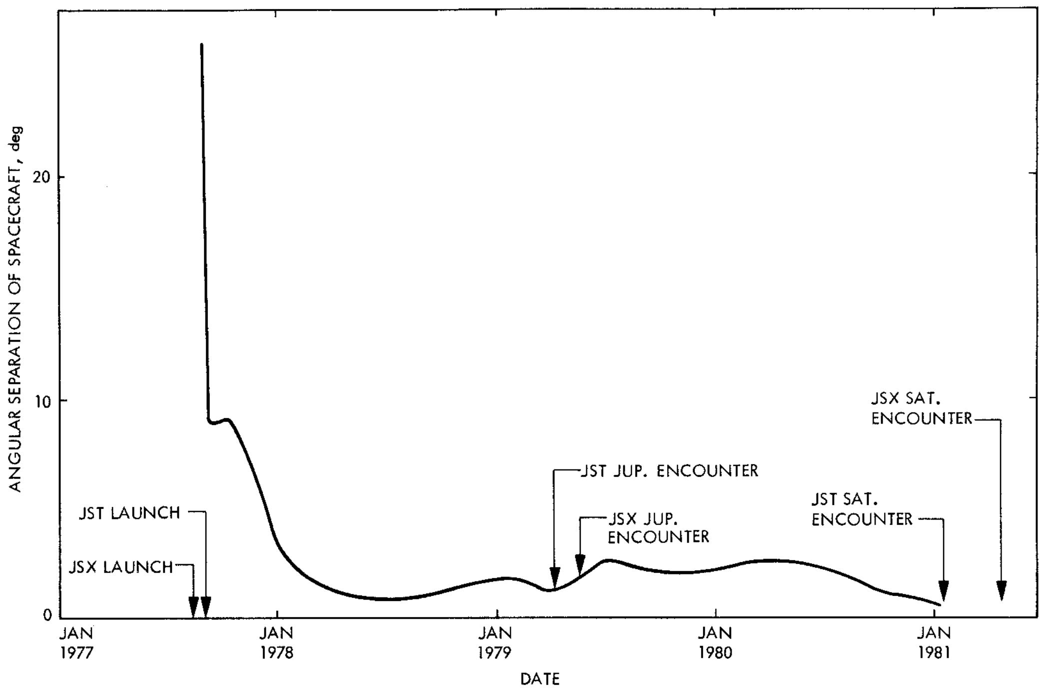

Fig. 7. Angular separation of JST and JSX spacecraft